Technical Paper 63

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FACTORS GOVERNING THE COMBUSTION OF COAL IN BOILER FURNACES

A PRELIMINARY REPORT

BY

J. K. CLEMENT, J. C. W. FRAZER

AND

C. E. AUGUSTINE

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FACTORS GOVERNING THE COMBUSTION OF COAL IN BOILER FURNACES; A PRELIMINARY REPORT.

By J. K. CLEMENT, J. C. W. FRAZER, and C. E. AUGUSTINE.

INTRODUCTION.

As a part of its investigation of the fuels belonging to or for the use of the United States and of methods of utilizing these fuels with greater efficiency, the Bureau of Mines has undertaken an investigation of the fundamental principles underlying the combustion of coal in boiler furnaces. A knowledge of these principles is requisite in order that furnaces may be properly designed and intelligently operated. The efficient use of coal is dependent on proper furnace design as well as on proper firing and control of the furnace. Many furnaces are built without regard to the special characteristics of the fuel to be used, with the result that for years fuel has been burned in an inefficient and wasteful manner, and so as to aggravate the smoke nuisance.

In the design of boiler furnaces the requirements of efficient combustion have been made secondary to many less important factors, largely because of a lack of definite information about the processes of combustion.

The combustion of coal may be considered as taking place in two stages: (1) Distillation of volatile matter and partial combustion on the grate, and (2) combustion in the combustion chamber of the gases rising from the grate. In order that the second stage of the process may be complete, it is essential that the combustible products given off from the fuel bed remain long enough in the combustion chamber to be entirely burned before they become chilled by contact with the relatively cold boiler surface. If the combustion space is too small the gases will pass out of it only partly burned, and a loss in heat and a lowering of efficiency will result.

It is believed that one result of a series of tests conducted by the Bureau of Mines, the beginning of which is here recorded, will be to make possible the more rational design of furnaces of many kinds, whatever the fuel burned, and thus to increase efficiency in the utilization of fuel.

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OBJECT OF INVESTIGATION.

Combustion is influenced by many factors, the most important of which are the following: The volume and shape of the combustion chamber; the kind of fuel used, especially the amount and character of the volatile matter and rate of firing; the rate of heating the fuel; the air supply; the rate at which air is mixed with the combustible gases in the furnace; and the temperature of the combustion chamber. The object of this investigation, outlined below, is to determine the conditions requisite for the complete combustion of the various types of coal in the United States.

SCOPE OF INVESTIGATION.

In general, the investigation includes a series of tests with each of five or six typical coals of the United States, each coal representing in chemical composition, especially as regards the amount and character of its volatile matter, the coal of a particular region.

The equipment designed for the tests comprises a furnace having between the fire box and the boiler a long combustion chamber of rectangular cross section. The furnace is provided with a mechanical stoker. In this furnace two factors can be varied at will, namely, the rate of firing and the air supply. The rate of heating of the coal and the rate of mixing of air with furnace gases are fixed by the design of the automatic stoker used.

After tests in the furnace used in the first part of the investigation have been completed, modifications in the furnace equipment will be made so as to permit variations in the rate of heating of the coal, in the manner of introducing air into the furnace, and in the form of the combustion chamber. Further tests will then be made to determine the influence of these factors on combustion.

This report embodies the results of a series of 23 tests with Pocahontas coal. In these tests the rate of firing was varied from 20 to 65 pounds of coal per square foot of grate area per hour, and the air supply was varied from 12 to 30 pounds of air per pound of combustible.

HISTORY OF THE INVESTIGATIONS.

The fuel-testing investigations now being conducted by the Bureau of Mines were, previous to the organization of the bureau in 1910, under the supervision of the United States Geological Survey. The investigations have included numerous tests with the various kinds of coal in the United States. One of the objects of these tests has been to determine the relative value of the kinds of coal for steaming purposes. The tests have been conducted with furnace equipment mainly of the hand-fired, plain-grate type, effort having been made

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always to regulate the furnace so as to burn each coal under the most favorable conditions. With the equipment available it has been impracticable to separate the data regarding the performance of the furnace from the data regarding the performance of the boiler.

From a study of the steaming tests made at the Government fuel-testing plant at St. Louis, Mo., in 1904–6, W. T. Ray and Henry Kreisinger, mechanical engineers in charge of the tests, concluded that an investigation of the fundamental principles underlying the combustion of coal in furnaces in general was greatly to be desired. With this end in view, the engineers mentioned proposed to construct a furnace having between the fire box and the boiler an unusually long combustion chamber in which the progress of the processes of combustion could be followed by determining the composition of the gases at various points in the furnace. Their recommendations were presented in the report of Prof. L. P. Breckenridge, chief of the steam-engineering division of the United States Geological Survey, to the national advisory board [a] at its meeting of April 10 and 11, 1906.

The plan received the approval of the advisory board, and upon the establishment of the Pittsburgh experiment station in the latter part of 1908 opportunity was given to carry out the investigation. The special furnace with the long combustion chamber was constructed in accordance with the plans of Messrs. Ray and Kreisinger, and, with the cooperation of J. C. W. Frazer and J. K. Clement, then with the survey but later connected with the Bureau of Mines, preliminary tests under their direction were begun in January, 1909. Mr. Ray later became engaged in other work, and the investigation was continued under the direction of a committee composed of Henry Kreisinger, mechanical engineer, chairman; J. C. W. Frazer, chemist; and J. K. Clement, physicist, until the summer of 1910. The experiments made in 1909 and the first half of 1910 were for the purpose of determining the number and character of observations and gas samples required to follow the processes of combustion in the experimental furnace. The method of procedure followed in the subsequent tests has been based on the results obtained in the preliminary experiments.

In October, 1910, Mr. Kreisinger left the service of the bureau. The series of tests with Pocahontas coal was then conducted by the authors of this report, Mr. Clement being chairman of the committee and C. E. Augustine being in immediate charge of the furnace and apparatus. The following employees of the bureau assisted in the tests: A. E. Hall and L. L. Satler, junior chemists; W. L. Egy, assistant physicist; and E. T. Gregg, physical laboratory aid.

[a] Appointed in 1906 to advise the United States Geological Survey concerning fuels and structural materials.

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EQUIPMENT AND CHARACTER OF TESTS.

DESCRIPTION OF FURNACE.

The unusually long combustion chamber of the furnace is about 43 feet in length over all. At one end is a Murphy mechanical stoker having a projected horizontal grate area of 25 square feet, as shown in figures 1 to 4.

The combustion chamber is tunnel like, being 3 feet wide, 2 feet 8 inches high, and 36 feet long, with double walls and an arched roof. The inner walls and the inner arch are 9 inches thick and are of the best quality of fire brick. The outer walls, 8 inches thick, are of common and pressed brick. In the sides a 2-inch air space separates the two walls; in the roof a 1-inch layer of magnesia blocks separates the two arches. Air leakage through the walls and roof is minimized by adjusting the speed of the pressure and exhaust fans so as to keep the pressure of the gases inside the combustion chamber slightly below that of the atmosphere. This method allowed observation through peep holes without trouble from jets of hot gases passing out. In the roof and at one side of the combustion chamber, at intervals of 5 feet, are holes for observing the temperature in the chamber and for inserting water-cooled gas samplers.

The exhaust fan is of sufficient capacity to maintain a 1½-inch draft (water) at the stack uptake from the boiler. The capacity of the pressure fan is sufficient to maintain about 1-inch pressure (water) in the ash pit.

The coal is delivered from bins to a platform built in front of and over the stoker, where it is weighed before being supplied to the stoker magazines.

METHOD OF OPERATION.

In the intervals between the tests herein reported, the furnace was operated continuously for the generation of steam in the power plant. Before each test all clinkers were removed from the fuel bed, and ash and refuse were removed from the ash pit. The test coal was then supplied to the magazines and fired at the rate determined for the test. The thickness of the fuel bed and the air supply were maintained as uniform as possible throughout the period of the test.

As a means of controlling the air supply, gas samples from the exit end of the combustion chamber were taken at intervals of about four minutes. By means of the Orsat apparatus the samples were analyzed for carbon dioxide and occasionally for oxygen.

Ellison differential draft gages were used for all draft observations. At 20-minute intervals readings were taken at the exit end of the furnace, over the fire, and in the ash pit.

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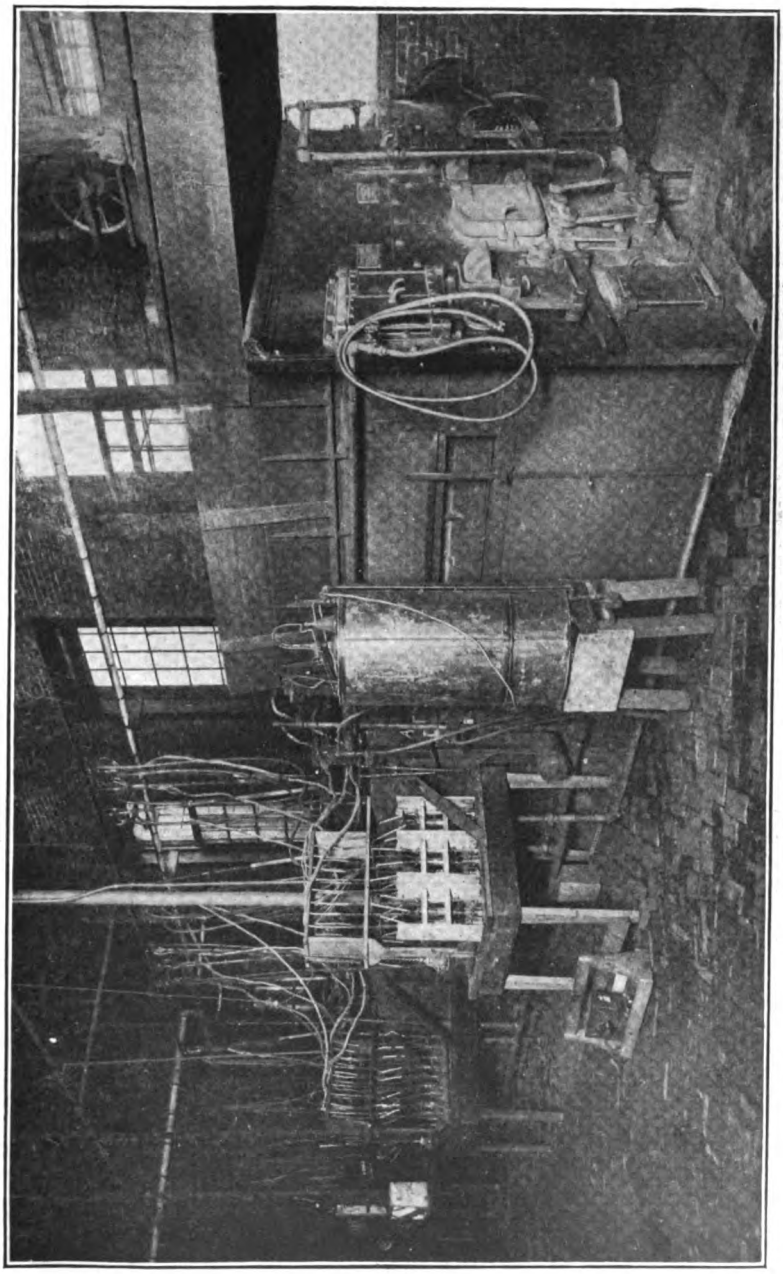

FIGURE 1.—General view of furnace.

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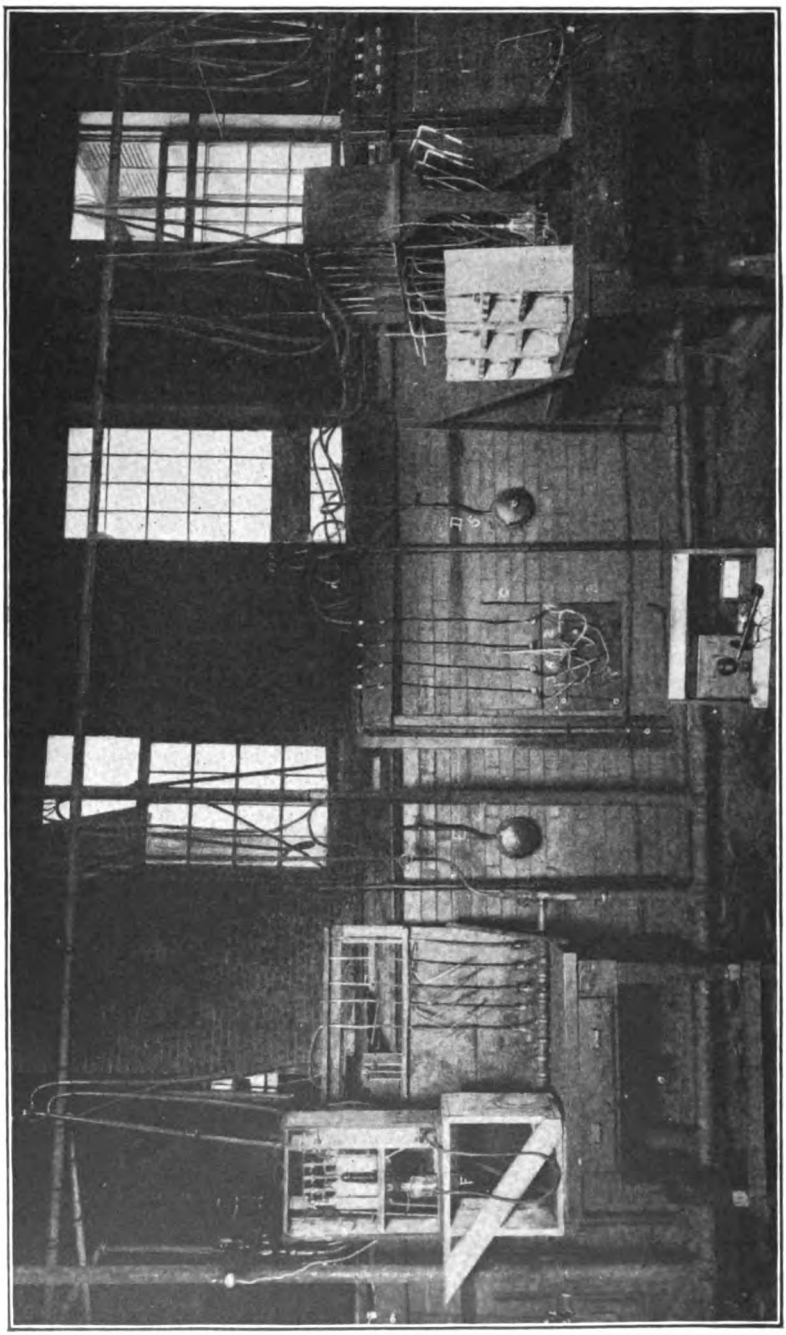

FIGURE 2.—View of combustion chamber, showing equipment for gas sampling.

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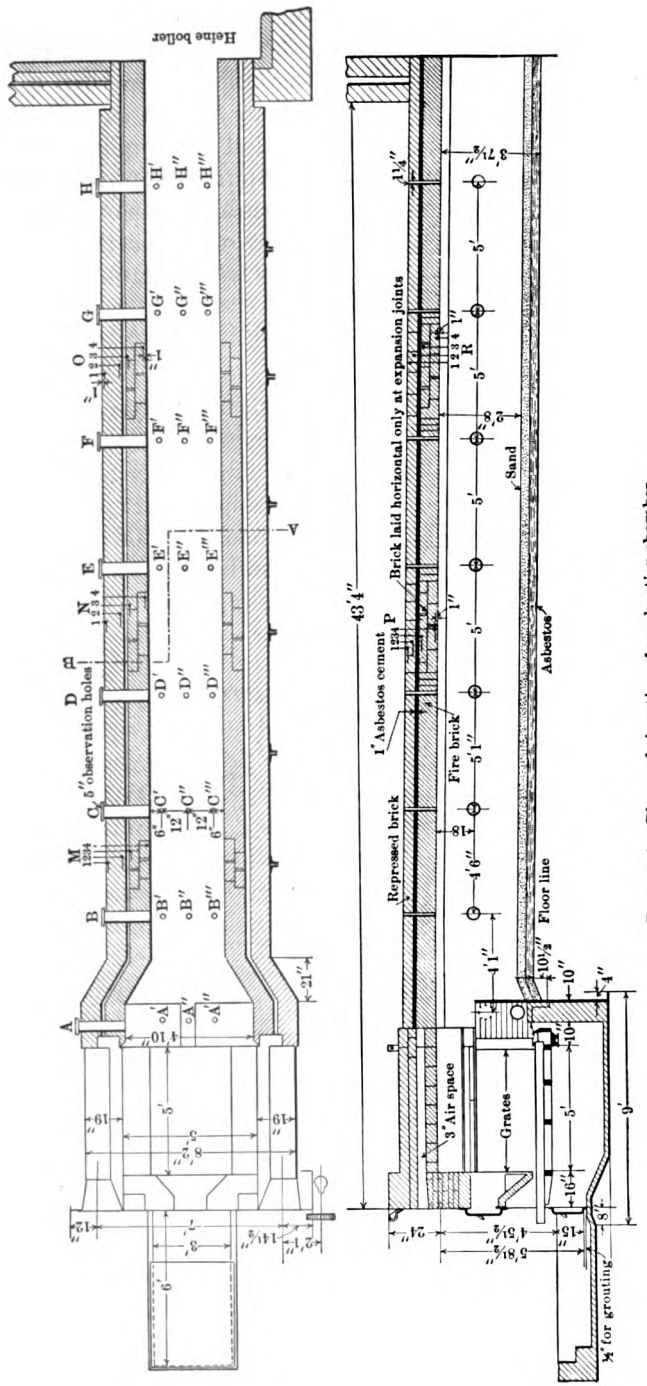

FIGURE 3.—Plan and elevation of combustion chamber.

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Before the general gas samples were taken the furnace was operated at the assigned rate for about three hours in order to allow the temperature of the combustion chamber to reach a condition of equilibrium. The water-cooled gas samplers were then introduced into the combustion chamber and 40 to 50 gas samples taken at various points in the furnace. The period of sampling was about 8 minutes. The test was continued for about 30 minutes after the gas samples had been obtained in order to show whether the furnace conditions were fluctuating.

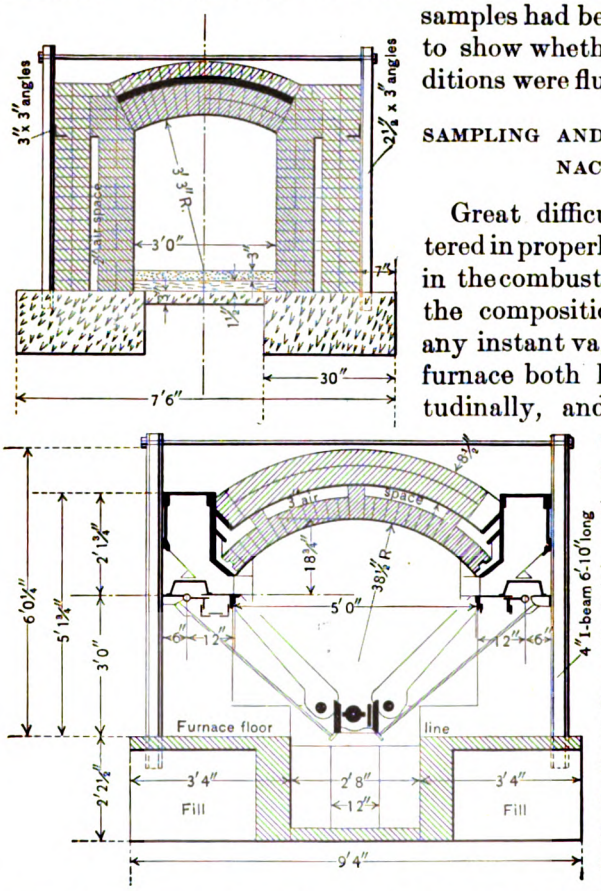

FIGURE 4.—Cross section of combustion chamber and of stoker. The chamber is connected to the setting of a 210-horsepower Heine boiler, the object being to cool the gases so that they can be handled by an exhaust fan.

SAMPLING AND ANALYSIS OF FURNACE GASES.

Great difficulties were encountered in properly sampling the gases in the combustion chamber because the composition of the gases at any instant varied throughout the furnace both laterally and longitudinally, and, further, because the combustion on the grate was never under complete control, so that the composition of the gases at any point in the combustion chamber varied in response to the changing conditions of the fire. It was necessary in this investigation to collect the samples of gas for analysis in such a way that a correct idea could be had of the composition of the furnace gases under the varying conditions. To correct for the variations that occurred across any section within the combustion chamber at any given instant, the number of samples collected at the section was made large and the points of collection were so distributed that the average of the analyses of the several samples at any section would give a fair average. To correct for the fluctuations that occurred as a result of the varying conditions of the fire, all the

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samples were collected over the same interval of time (about eight minutes) and in such a way that each sample would truly represent the average composition of the gases at the point from which it was drawn. The way in which this was accomplished is described below.

MANNER OF COLLECTING SAMPLES.

Gas samples were collected at eight cross sections of the combustion chamber, which have herein been designated A to H, A representing a section about 1 foot from the grate, and the letters B to H representing sections at intervals of 5 feet along the combustion chamber. At each of these sections three holes were made vertically through the arch of the chamber, one at the center of the arch and one on either side of and 1 foot from the central hole. The water-cooled tubes (fig. 5) through which gas was withdrawn for analysis were introduced through these holes in the arch. For convenience three sample tubes were mounted in one water jacket (fig. 5), the tubes extending to different depths in the furnace, so that three samples might be taken, one above the other. In this way three samples could be taken from each hole, or nine samples could be taken in each cross section at points uniformly distributed. (See fig. 3.)

APPARATUS FOR COLLECTING SAMPLES.

The apparatus for the collection of the gas samples is shown in figure 6. The part designated A in the figure is a water-cooled copper tube, one-eighth of an inch in diameter, to which a ¼-inch lead tube is connected by a short rubber tube. The lead tube is made long enough to be brought over to a table situated as near the furnace as possible and is there connected by a second short rubber tube to the upper end of a brass tube, B, the lower end of which dips beneath the water in the wash bottle. The brass tube, B, is perforated at a convenient height, and at this point a second brass tube, C, is soldered on. By applying suction to the wash bottle a rapid stream of gas is drawn from the furnace, the bubbling of the gas through the water in the wash bottle indicating at all times the flow of gas through the system. The glass reservoir, E, for collecting and retaining the sample for analysis is connected through the side tube, C, by means of the capillary glass tube, D, which fits snugly in C and is passed in until its open end is in the stream of gas flowing through B. Before beginning the collection of a sample, the reservoir, E, is filled with mercury and suction is applied to the wash bottle until all air is removed from the system. Before connecting D and E the air in D is removed by suction, and, with the connections made as shown in the illustration, the stopcocks of E are opened and the mercury allowed to drain out, the gas collecting above the mercury in E.

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As long as the surface of the mercury in E is above the lower end of the glass tube by which the gas gains entrance, the gas will enter E at a uniform rate and the sample will be representative. In order to regulate the period of sampling, a glass tube, drawn out at

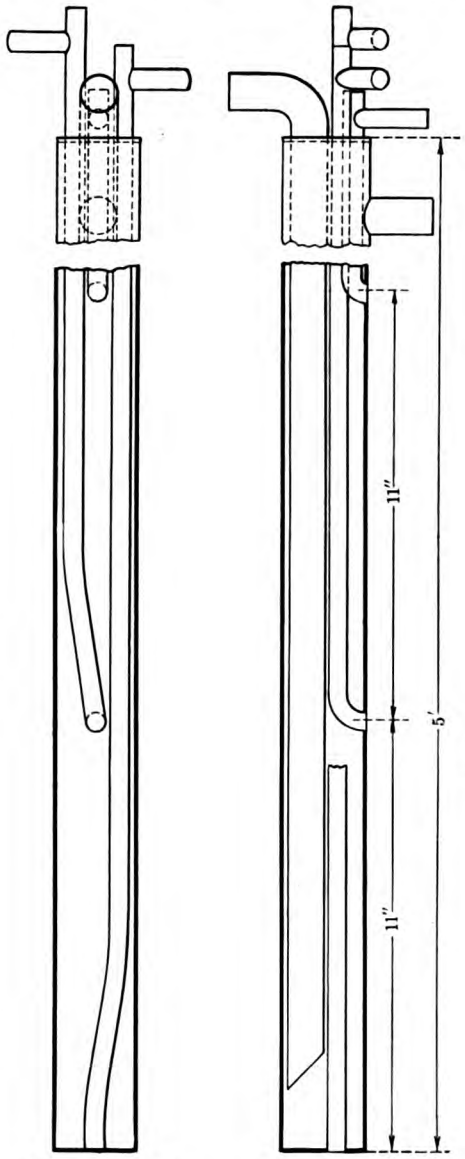

FIGURE 5.—Water-cooled gas sampler.

one end, is attached to the glass tube beneath the lower stopcock of E. This short tube is made so that by trial it will permit the flow of mercury from E in the desired length of time. In this way all the samples collected throughout the whole combustion chamber are collected

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during an equal period simultaneously, each sample representing the composition of the gas in the combustion chamber at the point from which it is withdrawn. For the sake of simplicity this description is made to cover the collection of a single sample. As stated above, it has been found convenient to place three tubes for gas collection in the same water jacket, the tubes opening at different distances along the jacket so that gas can be taken from three different levels. Figure 5 shows the arrangement for such a combination. Each water-cooled

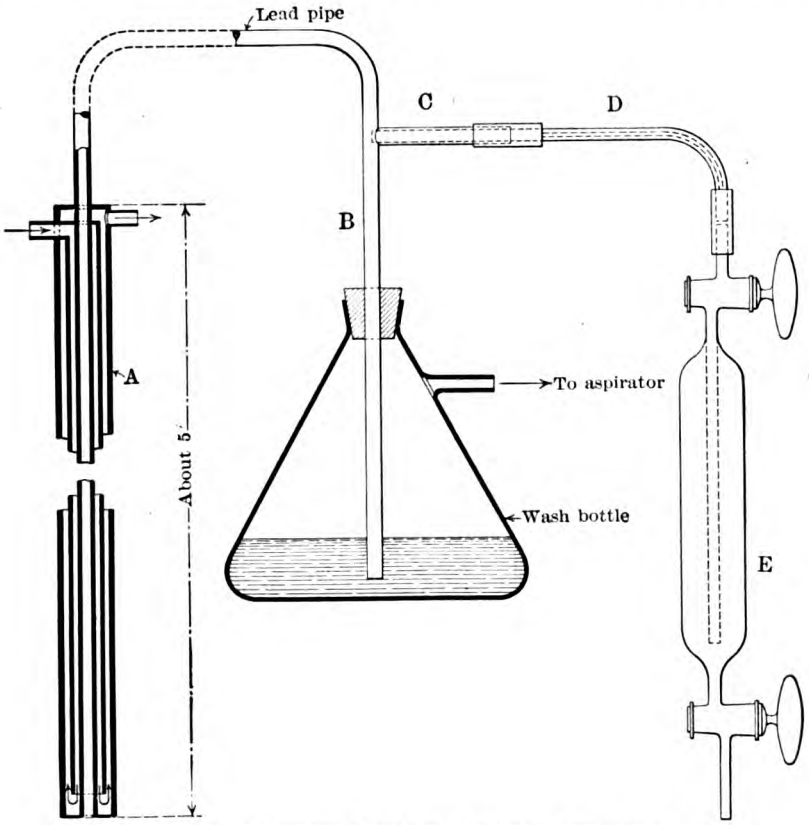

FIGURE 6.—Arrangement of apparatus for sampling furnace gases.

tube is connected to a separate system such as described above for a single sample. It has been found convenient to mount the glass vessels (E, fig. 6) permanently in wooden stands in batteries of three each, so that the three samples taken from each water-cooled jacket are contained in the same stand. After the collection of the samples the gas in each vessel is put under a pressure of about 100 mm. by running additional mercury through the lower stopcock, without introducing air into the vessel. As the gas is under a pressure

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greater than atmospheric and all communications to the exterior are sealed with mercury, there is no danger of leakage into or out of the vessel, and the analysis can be made when convenient.

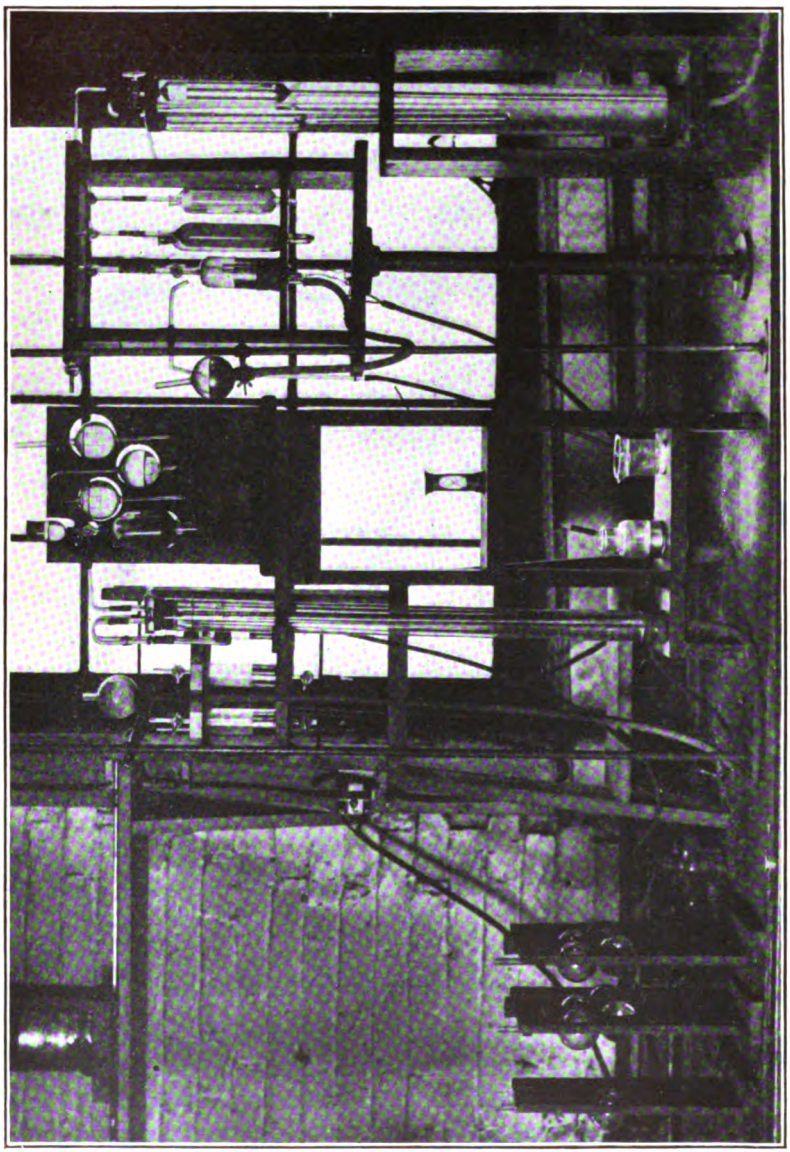

FIGURE 7.—Gas-analysis apparatus.

METHOD OF ANALYZING SAMPLES.

The gas samples collected as described above are analyzed by the method of Hempel, which embraces the use of water-jacketed burettes (fig. 7) filled with mercury and an inclosed mass of air for automatically

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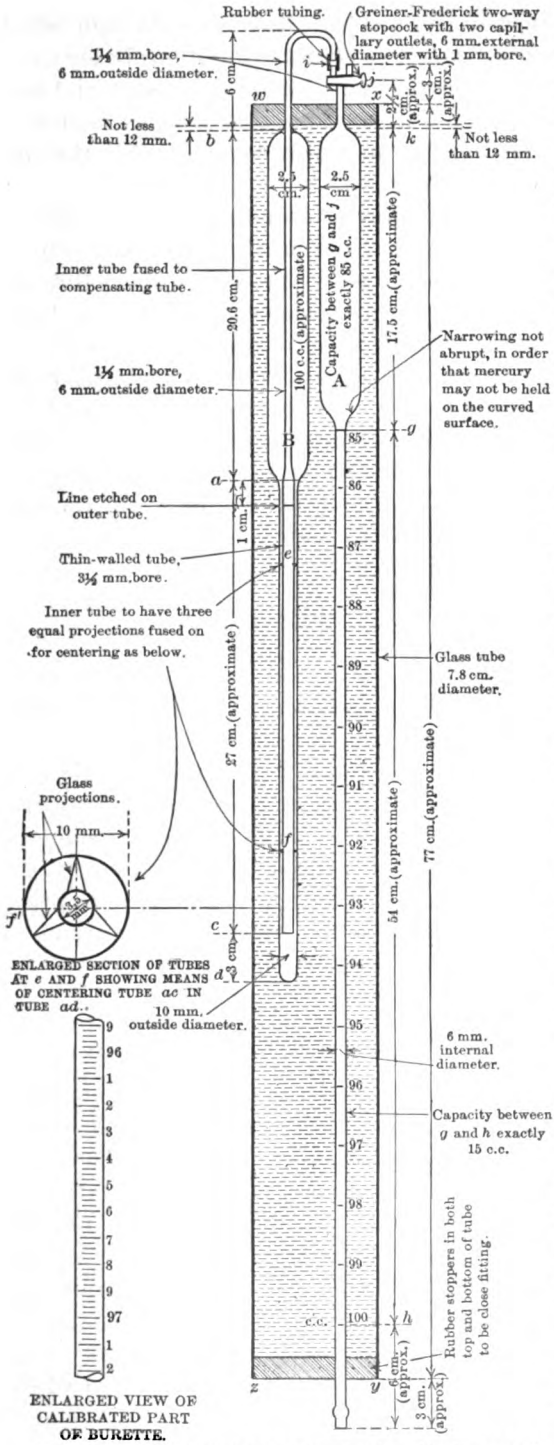
Rubber tubing.
Greiner-Frederick two-way stopcock with two capillary outlets, 6 mm. external diameter with 1 mm. bore.
1¼ mm. bore, 6 mm. outside diameter.
Not less than 12 mm.
Not less than 12 mm.
Inner tube fused to compensating tube.
1¼ mm. bore, 6 mm. outside diameter.
Line etched on outer tube.
Thin-walled tube, 3½ mm. bore.
Inner tube to have three equal projections fused on for centering as below.
Glass projections.
10 mm.
ENLARGED SECTION OF TUBES AT e AND f SHOWING MEANS OF CENTERING TUBE ac IN TUBE ad.
10 mm. outside diameter.
ENLARGED VIEW OF CALIBRATED PART OF BURETTE.
Capacity between g and f exactly 85 c.c.
100 c.c. (approximate)
Narrowing not abrupt, in order that mercury may not be held on the curved surface.
Glass tube 7.8 cm. diameter.
6 mm. internal diameter.
Capacity between g and h exactly 15 c.c.
Rubber stoppers in both top and bottom of tube to be close fitting.
20.6 cm.
27 cm. (approximate)
17.5 cm. (approximate)
54 cm. (approximate)
77 cm. (approximate)
1 cm.
c.c.

FIGURE 8.—Special burette for determination of hydrogen and methane.

25884°—14——3

compensating for changes of temperature and pressure. The determination of hydrogen and methane is made by the method of slow combustion, a burette of special construction, as shown in figure 8, being used. This burette is connected permanently to a system of stopcocks permitting connection with a combustion pipette, a caustic-potash pipette, and a pipette containing phosphorus or alkaline pyrogallate solution. By means of the burette, changes in volume amounting to 0.02 per cent can be measured. Samples of gas from the two sections of the combustion chamber nearest the firebox are analyzed for unsaturated hydrocarbons by absorption in fumic sulphuric acid.

In addition to the determination of the amount of unburned combustible gases accompanying a sample, efforts were made to determine the amount of carbon and hydrogen in the material that would be deposited from a known volume of the gas when suddenly cooled. This material constitutes

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the soot and tar that collect in the water-cooled tubes through which the gas is drawn from the combustion chamber, and probably tend to form smoke under ordinary conditions. Some of this material may be gaseous within the furnace, but condenses as soon as cooled to ordinary temperatures; much of it is probably carried bodily through the furnace by the rapidly moving gases.

In the efforts that have been made to determine the amount of smoke-forming material in the gases of the furnace, a known volume of gas was drawn from the desired point within the furnace through an asbestos filter contained in a water-cooled quartz-glass tube. After the quartz tube and its contents had been removed from the water-cooled jacket and dried to constant weight in an air bath, the tube and contents were placed in a combustion furnace and the combustible matter in the quartz tube and on the asbestos filter were burned as in the combustion of an organic substance. By this means, for a given point within the combustion chamber, the amount of unburned carbon and hydrogen that accompany a known volume of the furnace gases may be determined.

TEMPERATURE MEASUREMENTS.

Observations of the temperature within the combustion chamber and of the temperature of the flue gases were made at 20-minute intervals in all the tests. The flue-gas temperature was measured with a Hoskins thermocouple and a Leeds & Northrup portable telescope galvanometer, proper correction being applied for the temperature of the cold junction of the couple. Temperatures inside the combustion chamber were regularly measured through holes in the side wall at sections designated A and G in figure 3, a Wanner optical pyrometer being used. In addition to the regular observations of temperature at sections A and G, a number of sets of observations were made at sections A to G, inclusive.

TEMPERATURE IN COMBUSTION CHAMBER.

On account of the high temperatures in the combustion chamber in most of the tests, it was not practicable to measure the temperatures of the gases directly by means of thermocouples. The temperature indicated by the optical pyrometer is the temperature of the inner surface of the furnace wall. To determine the relation between the temperature of the wall as indicated by an optical pyrometer and the temperature indicated by a thermocouple suspended in the path of the furnace gases, a Hoskins thermocouple was introduced through the center of the arch at the section designated G in figure 3, so that its hot junction was at the center of the

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transverse section, and simultaneous observations were made with the Hoskins thermocouple and the Wanner pyrometer at the same section. The results are represented graphically in figure 9.

It is evident from the curves that the temperature of the wall follows closely that of the gases. This relation was determined only for those readings that were taken when there was no smoke present and the gases were transparent. The gases entering the combustion chamber carry with them in suspension more or less soot and tar, the substances that, when not completely burned in the combustion chamber, constitute smoke. When present in appreciable quantities, these substances form an opaque cloud that obscures the view of the wall beyond, and as the individual particles are incandescent it is the cloud of smoke that is seen by the optical pyrometer and not the furnace wall. The temperature indicated by the pyrometer is, then, the aver-

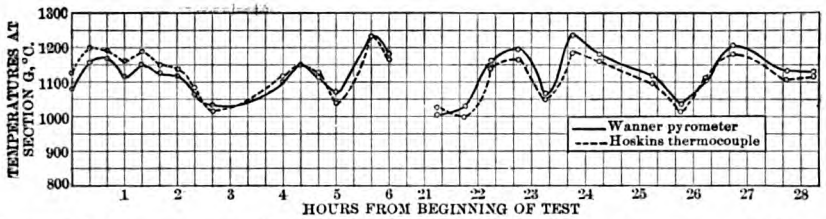

FIGURE 9.—Temperatures in combustion chamber as measured by Hoskins's thermocouple and Wanner's pyrometer.

age temperature of the particles composing the smoke. In this case, as the globules of tar or soot are hot from their own combustion and are heated by the surrounding gases, it is by no means certain that the temperature measured by the pyrometer is the average temperature of the gas and smoke passing through the combustion chamber.

COAL USED IN THE TESTS.

Two cars of semibituminous coal from the Norfolk mine, Pocahontas No. 3 bed, at Vivian, W. Va., designated as Pittsburgh 115 and Pittsburgh 148, were used in the tests. Pittsburgh 115 was used in tests 102 to 116 and Pittsburgh 148 in tests 117 to 125.

Proximate and ultimate analyses and determinations of calorific value were made of the car samples of each coal. During each test a sample of 100 pounds was collected and a part was submitted for proximate analysis and calorific-value determination. The results of analyses of the two car samples, together with the averages of the test samples, are given in the table following.

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Analyses of coal used in the tests.

PROXIMATE ANALYSIS.

Constituent.	Pittsburgh 115.		Pittsburgh 148.	
	Car sample.	Average of test samples.	Car sample.	Average of test samples.
Moisture.....per cent..	2.21	1.53	2.97	1.45
Volatile matter.....do....	15.78	16.30	15.87	15.79
Fixed carbon.....do....	71.65	72.20	71.39	72.18
Ash.....do....	10.36	9.97	9.77	10.58
	100.00	100.00	100.00	100.00

ULTIMATE ANALYSIS.

Hydrogen.....per cent..	4.08	.....	4.33	.....
Carbon.....do....	79.11	.....	79.41	.....
Nitrogen.....do....	1.04	.....	.99	.....
Oxygen.....do....	4.86	.....	4.98	.....
Sulphur.....do....	.55	.....	.52	.....
Ash.....do....	10.36	.....	9.77	.....
	100.00	.....	100.00	.....
Calorific value, B. t. u. per pound.....	13756	13909	13768	13811

This coal burned rapidly, caked, and required careful attention to prevent the formation of holes and cracks in the fuel bed. Clinkers formed at times,but they did not stick to the grate and were easily removed.

SIZE OF COAL.

The coal was screened at the mine, the size used being that which passed over a ¾-inch and through a 1½-inch bar screen, but owing to handling and shipping some of it was broken into small particles, as shown by the following results of a sizing test:

Results of sizing test of coal.

Size of holes in screen.	Quantity of coal that passed through screen.		Weight of coal determining average size (column 1 × column 3).
	Actual.	Reduced to 100-pound basis.	
1	2	3	4
Inch.	*Pounds.*	*Pounds.*	*Pounds.*
¼	3.0	4.9	0.6
½	3.0	4.9	1.2
¾	3.5	5.7	2.9
1	38.0	62.4	62.4
1½	13.5	22.1	33.1
.....	61.0	100.0	100.2

Average diameter of coal, $\frac{100.2}{100}$=1 inch.

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METHOD OF SAMPLING.

A car sample of about 60 pounds, taken at the time of unloading, was sent to the chemical laboratory for proximate and ultimate analysis and determination of heat units. During each test a sample of about 100 pounds was collected and a part of it submitted for proximate analysis and determination of heating value. A sample of ash was collected at the close of each test and a proximate analysis of it was made.

RESULTS OF THE EXPERIMENTS.

PRELIMINARY EXPERIMENTS.

Before a systematic study of various coals was begun, a series of preliminary tests was made for the purpose of studying the characteristics of the special furnace equipment and of determining the method to be followed in subsequent tests. The first series of 16 tests was with Pittsburgh slack coal, fired at the rate of about 25 pounds per square foot of grate area per hour. Attention was given principally to the degree of homogeneity of the gas mixture at various distances from the grate, in order to ascertain the number of gas samples that should be taken at the different transverse sections to give a correct value for the average composition of the furnace gases. The results of the preliminary experiments indicated that to follow properly the progress of combustion during the passage of the gases through the furnace it would be necessary to take between 40 and 50 gas samples.

With the preliminary study of the progress of combustion in the furnace, observations were taken of the temperature gradient through the furnace walls as bearing on the question of the loss of heat by radiation. The results of the observations have been published by Ray and Kreisinger.[a]

TESTS OF POCAHONTAS COAL.

In the tests with Pocahontas coal described in this report two factors were independently varied—the rate of firing and the air supply. The rate of firing was varied from 20 to 65 pounds of coal per square foot of grate area per hour. A series of three or more tests was made with each rate of firing, the tests in each series being run with different air supply.

The variations in furnace conditions during a single test and the character of observations taken are indicated in figure 10, which presents the observations of test 121. In this test an effort was made to maintain a low air supply and consequently a high percentage of CO_2 in the furnace gases. Although the average percent-

[a] Ray, W. T., and Kreisinger, Henry, The flow of heat through furnace walls: Bull. 8, Bureau of Mines, 1911. 32 pp.

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age of CO_2 is high it will be noted that the value fluctuated from 12.5 to 17.5 per cent. It may be stated here that the greatest difficulty encountered in the operation of the furnace was the proper control of the air supply, fluctuations of 3 to 5 per cent seemingly being unavoidable. The fluctuations were due, in part at least, to the caking tendency of the coal and the formation of holes in the

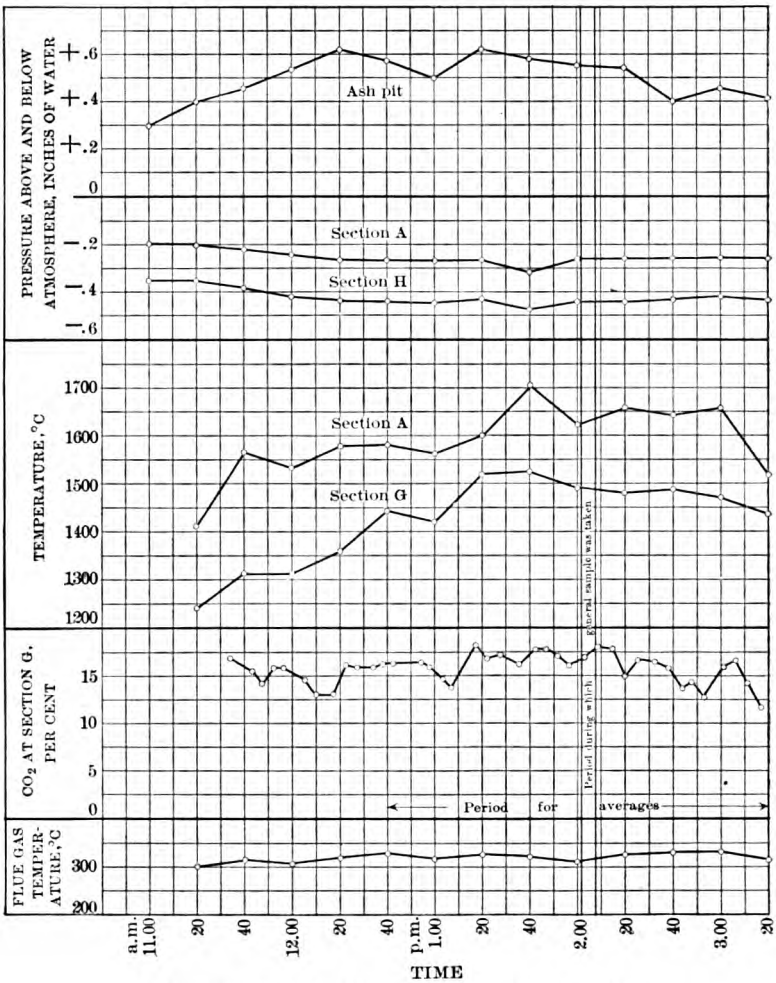

FIGURE 10.—Variations in furnace conditions during test 121.

fire, and also to inadequate provision for admission of air over the top of the fuel bed, for the higher rates of combustion, in the type of stoker used.

The composition of gases at various points in the combustion chamber in test 121 is given in Table 1. The samples were collected simultaneously, over a period of six minutes, in the manner described in page 13. The letters in the first column indicate the transverse

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section through the combustion chamber at which the samples were taken. Section A represents the section nearest the grate and section H that farthest from the grate, the intervals between consecutive sections being 5 feet. The table follows:

TABLE 1.—*Composition*[a] *of combustion gases at various points in the combustion chamber.*

Section.	Gas.	Distance below arch in hole 1.[b]			Distance below arch in hole 2.[c]			Distance below arch in hole 3.[d]			Average.			
		5 inches.	16 inches.	27 inches.	5 inches.	16 inches.	27 inches.	5 inches.	16 inches.	27 inches.	5 inches.	16 inches.	27 inches.	Average.
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
A	CO_2	16.8	13.9	14.4	16.6	14.7	16.3	15.9	13.1	7.3	16.3	13.9	12.7	14.3
	O	.6	3.3	.5	.5	1.0	.0	1.5	1.5	.3	.9	1.9	.3	1.0
	CO	2.8	.7	8.0	3.6	7.0	6.0	1.9	6.7	17.5	2.8	4.8	10.5	6.0
	CH_4	.0	.0	.0	.2	.3	.0	.1	.2	.5	.1	.2	.2	.1
	H	.6	.0	2.3	.4	1.3	1.6	.0	1.0	5.1	.3	.8	3.0	1.4
	Total													22.8
B	CO_2	17.0	16.3	14.6	16.3	15.6	16.2	16.6	14.7	14.7	16.6	15.5	15.2	15.8
	O	.3	.9	3.8	.2	.0	1.1	2.0	2.3	.4	.8	1.1	1.8	1.2
	CO	2.9	3.0	.0	4.5	4.2	2.1	.7	2.2	5.3	2.7	3.1	2.5	2.8
	CH_4	.0	.0	.0	.2	.1	.0	.0	.3	.3	.1	.1	.1	.1
	H	.9	.8	.4	.8	.8	.9	.2	.2	1.0	.6	.6	.7	.7
	Total													20.5
C	CO_2	16.2	17.0	16.8	14.2	17.0	16.3				15.2	17.0	16.6	16.3
	O	.3	.7	1.8	5.5	.9	2.5				2.9	.8	2.2	2.0
	CO	4.9	1.6	.3	.0	.5	.3				2.5	1.1	.3	1.3
	CH_4	.0	.0	.0	.0	.2	.3				.0	.1	.1	.1
	H	1.0	.7	.4	.1	.0	.0				.6	.4	.2	.4
	Total													20.1
D	CO_2				17.0	16.4	17.2				17.0	16.4	17.2	16.9
	O					1.2	1.3					1.2	1 3	1.3
	CO					.3	.7					.3	.7	.5
	CH_4					.1	.1					.1	.1	.1
	H					.4	.4					.4	.4	.4
	Total													19.2
E	CO_2					17.0						17.0		17.0
	O					1.0						1.0		1.0
	CO					.7						.7		.7
	CH_4					.2						.2		.2
	H					.0						.0		.0
	Total													18.9
F	CO_2					17.5						17.5		17.5
	O					1.0						1.0		1.0
	CO					.1						.1		.1
	CH_4					.0						.0		.0
	H					.5						.5		.5
	Total													19.1
G	CO_2					17.6						17.6		17.6
	O					.8						.8		.8
	CO					.2						.2		.2
	CH_4					.1						.1		.1
	H					.2						.2		.2
	Total													18.9
H	CO_2		17.7	16.6	17.6	17.5	17.8	16.2	17.6	16.9	16.9	17.6	17.1	17.2
	O		1.2	2.4	.9	1.0	1.4	2.5	.9	1.1	1.7	1.0	1.6	1.4
	CO		.0	.0	.1	.2	.0	.0	.0	.3	.1	.1	.1	.1
	CH_4		.1	.0	.0	.0	.1	.0	.0	.0	.0	.0	.0	.0
	H		.0	.0	.3	.0	.1	.1	.6	.4	.2	.2	.2	.2
	Total													19.1

[a] Proportion of nitrogen (by difference) is not included in this list.
[b] Midway between center and left side wall.
[c] Extended vertically through middle of sections.
[d] Midway between center and right side wall.

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The last column of the table gives the average composition for each section and is the mean of the compositions of the individual samples obtained at the section.

These average analyses are plotted as ordinates in figure 11, the abscissas being the volume of combustion chamber through which

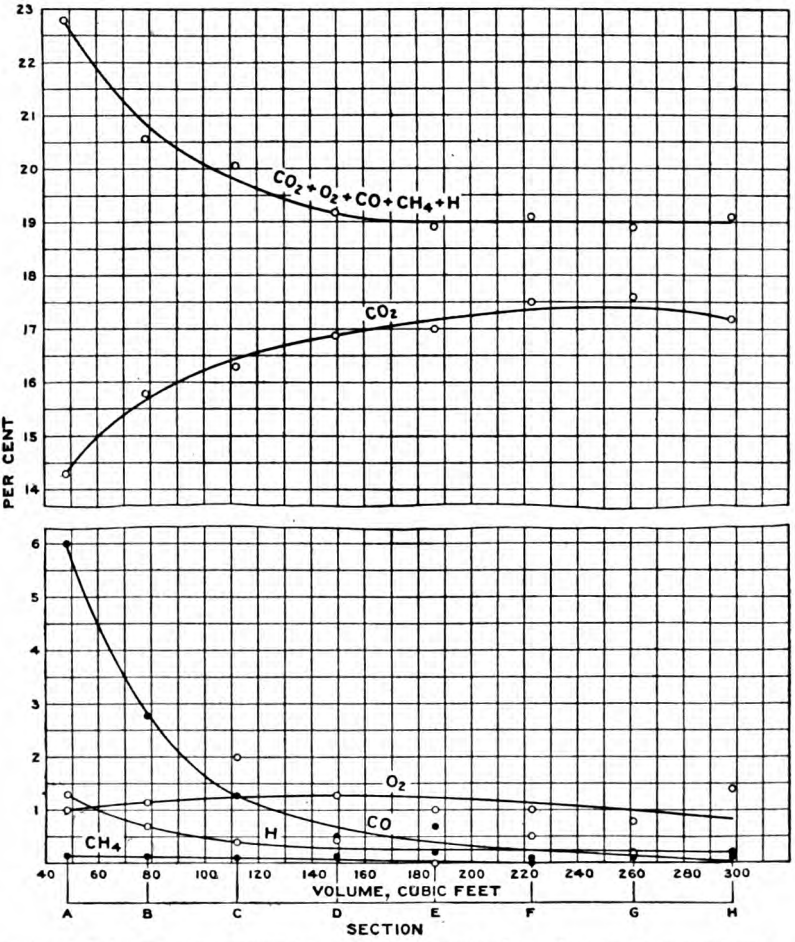

FIGURE 11.—Relation between composition of furnace gas and volume of combustion space through which gas has passed, test 121. Rate of firing, 61 pounds per square foot of grate area per hour.

the gas has traveled. The curve drawn through the points for a particular component of the furnace gas shows the rate at which the component increases or decreases as the gas travels through the furnace.

The results of the tests with Pocahontas coal are given in Tables 2 and 3.

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TABLE 2.—*Results of first series of long combustion chamber tests with semibituminous, steaming coal from Norfolk mine, Pocahontas No. 3 bed, Vivian, W. Va. (Pittsburgh 115).*

Test No.	Coal per square foot of grate area per hour.	Air supply.		Temperature at section G.	Average contents of CO_2, O_2, and CO in gas.			
		Per pound of combustible consumed.	Excess.		Section.	CO_2.	O_2.	CO.
	Pounds.	*Pounds.*	*Per cent.*	*° C.*		*Per cent.*	*Per cent.*	*Per cent.*
102	30.5	15.79	32.91	1480	A	12.0	4.7	3.8
					B	13.3	5.4	.4
					C	11.7	5.6	.0
					D	12.4	6.6	.0
					E	13.4	5.1	.0
					F	13.6	5.3	.0
					G	14.1	4.7	.0
103	28.0	25.74	116.67	1269	A	10.5	7.5	2.0
					B	5.9	10.1	.0
					C	8.0	9.8	.0
					D	9.6	8.7	.0
					E	8.4	9.3	.0
					F	8.6	9.2	.0
					G	8.7	9.6	.0
104–1	29.3	21.66	82.32	1239	A	10.3	6.3	2.9
					B	11.1	7.9	.0
					C	7.8	11.5	.0
					D	10.4	8.1	.5
					E	10.2	8.8	.0
					F	10.1	8.0	.0
					G	10.2	9.2	.0
104–2	29.3	19.03	60.19	1239	A	11.2	5.9	2.2
					B	12.5	6.1	.4
					C	10.3	8.9	.0
					D	11.6	7.1	.0
					E	11.1	7.5	.0
					F	11.5	6.8	.0
					G	11.7	7.1	.0
105–1	28.0	16.61	39.81	1352	A	13.2	3.2	3.3
					B	14.3	4.2	.0
					C	12.2	6.2	.0
					D	13.8	4.9	.0
					E	13.1	5.6	.0
					F	13.4	5.6	.0
					G	13.4	5.4	.0
105–2	28.0	14.46	21.72	1352	A	13.0	2.5	5.7
					B	15.1	3.7	.4
					C	13.9	5.2	.0
					D	15.4	3.9	.0
					E	15.5	3.5	.0
					F	15.5	3.7	.0
					G	15.3	4.0	.0
106–1	28.0	13.59	14.39	1451	A	11.5	2.2	8.4
					B	15.0	2.5	1.0
					C	16.4	1.9	.2
					D	16.4	2.6	.0
					E	16.0	2.8	.0
					F	15.8	3.6	.0
					G	16.3	2.9	0
106–2	28.0	14.38	21.04	1451	A	13.9	2.2	5.0
					B	15.3	3.3	.1
					C	15.1	4.0	.0
					D	15.2	3.7	.0
					E			
					F	15.6	3.3	.0
					G	15.4	3.8	.0
107–1	27.2	31.12	161.95	1143	A	9.3	9.4	.4
					B	7.9	11.9	.2
					C	8.8	10.9	.0
					D	7.0	12.6	.0
					E	7.0	12.7	.0
					F	7.3	12.5	.0
					G	7.1	12.3	.0
107–2	27.2	29.79	150.76	1143	A	9.7	9.6	.1
					B	8.6	11.2	.0
					C	8.0	12.0	.0
					D	7.6	10.9	.0
					E	7.7	11.8	.0
					F	7.4	12.1	.0
					G	7.4	12.2	.0

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TABLE 2.—*Results of first series of long combustion chamber tests with semibituminous, steaming coal from Norfolk mine, Pocahontas No. 3 bed, Vivian, W. Va. (Pittsburgh 115)*—Continued.

Test No.	Coal per square foot of grate area per hour.	Air supply.		Temperature at section G.	Average contents of CO_2, O_2, and CO in gas.			
		Per pound of combustible consumed.	Excess.		Section.	CO_2.	O_2.	CO.
	Pounds.	*Pounds.*	*Per cent.*	*° C.*		*Per cent.*	*Per cent.*	*Per cent.*
108-1	22.2	15.67	31.90	1253	A	13.4	6.0	0.7
					B	14.1	5.5	.0
					C	13.2	5.5	.7
					D	14.1	5.2	.0
					E	14.2	4.3	.6
					F	14.4	5.0	.0
					G	14.1	5.3	.0
108-2	22.2	14.98	26.09	1253	A	14.1	3.7	2.4
					B	15.2	3.0	.0
					C	14.7	3.4	.0
					D	14.6	3.5	.0
					E	15.0	3.6	.0
					F	14.9	3.6	.0
					G	14.9	3.7	.0
109-1	20.0	27.14	128.45	986	A	8.3	10.6	.8
					B	6.8	11.6	.3
					C	7.5	10.6	.1
					D	9.1	11.3	.0
					E	.....	.....	.....
					F	8.3	11.2	.0
					G	8.1	11.7	.0
109-2	20.0	25.63	115.74	986	A	7.3	10.2	3.5
					B	6.9	12.4	.3
					C	8.6	11.0	.0
					D	8.6	10.8	.0
					E	8.4	11.0	.0
					F	8.5	11.1	.0
					G	8.6	11.0	.0
110-1	20.6	13.46	13.30	1278	A	15.2	4.1	1.6
					B	15.1	4.5	.2
					C	14.0	5.2	.0
					D	16.3	2.7	.0
					E	16.2	2.7	.0
					F	17.8	1.5	.0
					G	16.4	3.1	.0
110-2	20.6	12.89	8.50	1278	A	15.1	2.4	4.5
					B	15.1	3.6	1.2
					C	13.5	5.2	.1
					D	16.7	1.8	.0
					E	16.1	2.7	.0
					F	17.2	1.7	.0
					G	17.2	1.9	.0
111-1	38.1	16.63	39.98	1344	A	12.6	5.3	2.2
					B	15.0	3.2	1.5
					C	12.5	6.0	.0
					D	13.0	5.3	.9
					E	.....	.....	.....
					F	.....	.....	.....
					G	.....	.....	.....
					H	13.4	5.3	.0
111-2	38.1	17.15	44.36	1344	A	12.6	5.7	1.6
					B	13.3	3.6	1.5
					C	.....	.....	.....
					D	12.7	6.3	.0
					E	14.4	4.2	.0
					F	14.5	4.6	.1
					G	13.2	5.3	.0
					H	12.6	6.4	.3
112-1	36.7	13.38	12.63	1416	A	15.0	3.0	2.5
					B	16.3	2.4	.9
					C	15.7	3.4	.0
					D	.....	.....	.....
					E	.....	.....	.....
					F	.....	.....	.....
					G	.....	.....	.....
					H	16.6	2.4	.0

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TABLE 2.—*Results of first series of long combustion chamber tests with semibituminous, steaming coal from Norfolk mine, Pocahontas No. 3 bed, Vivian, W. Va. (Pittsburgh 115)*—Continued.

Test No.	Coal per square foot of grate area per hour.	Air supply.		Temperature at section G.	Average contents of CO_2, O_2, and CO in gas.			
		Per pound of combustible consumed.	Excess.		Section.	CO_2.	O_2.	CO.
	Pounds.	*Pounds.*	*Per cent.*	*° C.*		*Per cent.*	*Per cent.*	*Per cent.*
					A	14.0	4.1	3.4
					B	15.9	1.5	1.2
					C	15.9	1.9	.0
					D			
112–2	36.7	14.07	18.43	1416	E			
					F			
					G			
					H	16.0	1.9	
					A	8.7	6.5	7.0
					B	10.7	6.5	2.9
					C	12.5	6.4	.0
					D			
113–1	36.8	17.08	43.77	1264	E			
					F			
					G			
					H	13.1	5.3	.0
					A	7.8	7.8	7.7
					B	10.2	7.8	2.6
					C	11.6	6.8	.5
					D	12.3	6.3	.0
113–2	36.8	15.98	34.51	1264	E			
					F			
					G			
					H	13.9	5.1	.0
					A	14.0	3.3	4.7
					B	15.6	3.3	.1
					C	15.1	3.8	.0
					D			
114	44.0	14.29	20.29	1443	E			
					F			
					G			
					H	15.6	3.1	.0
					A	12.1	5.3	3.1
					B	13.3	6.0	.2
					C	14.0	5.1	.0
					D			
115	43.2	12.04	43.43	1403	E			
					F			
					G			
					H	13.0	6.2	.0
					A	11.2	8.9	1.9
					B	11.5	7.8	.2
					C	11.4	7.9	.1
					D	11.6	7.6	.0
116	42.8	21.25	78.87	1302	E			
					F			
					G			
					H	10.4	9.0	.0

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TABLE 3.—*Results of first series of long combustion chamber tests with semibituminous, steaming coal from the Norfolk mine, Pocahontas No. 3 bed, Vivian, W. Va. (Pittsburgh 148).*

Test No.	Coal per square foot of grate area per hour.	Air supply.		Temperature at section G.	Average composition of gas.[a]						Combustible gases.
		Per pound of combustible consumed.	Excess.		Section.	CO_2.	O_2.	CO.	CH_4.	H_2.	
	Pounds.	*Pounds.*	*Per ct.*	*°C.*		*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
					A	12.7	1.5	8.2	0.3	1.1	9.6
					B	15.4	.9	4.1	.5	.7	5.3
					C	15.9	.7	3.1	.4	.7	4.2
117	43.4	11.20	−6.90	1441	D	16.8	.7	.6	.6	.4	1.6
					E	16.2	.2	1.9	.....	.....	.....
					F	17.0	.6	1.2	.5	.0	1.7
					G	16.8	.4	1.8	.6	.4	2.8
					H	16.7	.3	2.7	.2	.5	3.4
					A	14.4	2.2	5.2	.2	.7	6.0
					B	16.4	1.7	2.5	.4	.2	3.1
					C	16.5	1.9	1.4	.3	.0	1.7
118	45.8	12.61	4.82	1451	D	16.9	1.9	.4	.....	.....	.4
					E	17.3	1.4	.1	.....	.....	.1
					F	17.1	1.8	.0	.....	.....	.0
					G	17.5	1.4	.0	.....	.....	.0
					H	17.2	1.7	.1	.3	.0	.4
					A	12.7	6.3	1.0	.4	.2	1.7
					B	12.7	6.8	.0	.0	.0	.0
					C	12.6	7.1	.0	.....	.....	.0
119	47.1	18.15	50.87	1338	D	.....	.....	.....	.....	.....	.....
					E	.....	.....	.....	.....	.....	.....
					F	.....	.....	.....	.....	.....	.....
					G	.....	.....	.....	.....	.....	.....
					H	12.2	7.5	.0	.....	.....	.0
					A	13.7	2.5	5.5	.2	1.1	6.8
					B	15.9	1.8	1.9	.1	.4	2.4
					C	15.5	3.0	.8	.2	.1	1.1
120	55.7	13.89	15.46	1436	D	15.0	3.3	.3	.0	.0	.3
					E	15.7	2.8	.0	.0	.0	.....
					F	15.7	2.8	.1	.1	.0	.2
					G	16.1	2.4	.1	.1	.0	.2
					H	15.9	2.8	.2	.0	.0	.2
					A	14.3	1.0	6.0	.1	1.4	7.5
					B	15.8	1.2	2.8	.1	.6	3.5
					C	16.3	2.0	1.3	.1	.4	1.8
121	61.0	12.91	7.32	1475	D	16.9	1.3	.5	.0	.4	.9
					E	17.0	1.0	.7	.2	.0	.9
					F	17.5	1.0	.1	.0	.5	.6
					G	17.6	.8	.2	.1	.2	.5
					H	17.2	1.4	.1	.0	.2	.2
					A	13.0	5.7	1.9	.1	.2	2.2
					B	13.0	6.8	.0	.0	.2	.3
					C	11.4	8.2	.0	.0	.0	.0
123	58.2	21.27	76.81	1244	D	.....	.....	.....	.....	.....	.....
					E	.....	.....	.....	.....	.....	.....
					F	.....	.....	.....	.....	.....	.....
					G	.....	.....	.....	.....	.....	.....
					H	10.4	9.4	.0	.0	.0	.0
					A	12.3	6.3	2.2	.2	.2	2.6
					B	13.1	6.3	.1	.0	.0	.1
					C	12.8	6.6	.0	.0	.0	.0
124	58.9	20.00	66.25	1318	D	.....	.....	.....	.....	.....	.....
					E	.....	.....	.....	.....	.....	.....
					F	.....	.....	.....	.....	.....	.....
					G	.....	.....	.....	.....	.....	.....
					H	11.1	8.4	.0	.0	.0	.0
					A	10.6	3.8	8.2	.2	1.4	9.8
					B	14.9	2.0	3.3	.2	.4	3.9
					C	14.3	3.9	1.1	.1	.2	1.4
125	66.5	13.24	10.06	1386	D	15.9	2.0	1.0	.1	.3	1.4
					E	15.3	2.3	.7	.0	.2	.9
					F	16.4	2.0	.4	.0	.1	.5
					G	13.5	5.4	.4	.1	.0	.5
					H	16.5	2.3	.3	.0	.1	.4

[a] Nitrogen content (by difference) not given.

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The values for the composition of the furnace gases were obtained by taking the mean of the values found for the individual samples at each of the several sections. In tests 104 to 113 two sets of samples were taken. As the advantages of having the second set of samples did not appear to compensate for the additional labor of analyzing them, the second set was not taken in subsequent tests.

AIR SUPPLY.

The values for air supplied per pound of combustible consumed, given in the third column of Tables 2 and 3, were calculated by means of the formula

$$A_s = 3.03C\frac{N_2}{(CO_2+CO+CH_4)},$$

in which A_s = pounds of air supplied per pound of combustible consumed;

C = pounds of carbon in 1 pound of "moisture and ash free" coal;

N_2, CO_2, CO, and CH_4 = percentages in the furnace gases at section H.

The values for excess of air supply, given in the fourth column of Tables 2 and 3, are calculated from the formula

$$\text{Percentage of excess air} = 100\times\frac{A_s - A_r}{A_r}$$

In this formula A_r, the "pounds of air required for the combustion of 1 pound of combustible," is computed from the ultimate analysis of the car sample of the coal by means of the formula

$$A_r = 34.48H + 11.58C + 4.336\,(S-O),$$

in which H, C, S, and O are the percentages in the coal on the "moisture and ash free" basis, divided by 100.

The expressions for air supplied and air required are not exact, because (1) they rest on the assumption that the composition of the combustible matter in the refuse is the same as the composition of the "combustible" in the fuel as fired; (2) no correction is made for the combustible matter carried in the furnace gas in liquid or solid form; and (3) no correction is made for the nitrogen in the coal. The assumption that the composition of the combustible matter in the refuse is the same as the composition of the "combustible" in the fuel as fired is obviously not correct, for a large part of the volatile matter of the combustible that falls through the grate is driven off and carried into the combustion chamber. Consequently the weight of carbon in the furnace gas per pound of combustible consumed is somewhat less than the value C, which is obtained from the ultimate

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analysis of the car sample of the coal. The error from this assumption regarding the combustible matter in the refuse is probably not over 1 per cent, as the following calculation indicates:

Let C=pounds of carbon in 1 pound of combustible as fired;
A=pounds of carbon in refuse per pound of combustible fired;
and B=pounds of "combustible" in refuse per pound of combustible fired.
Then C−A=pounds of carbon in furnace gas per pound of combustible fired,
and $\frac{C-A}{1-B}$=pounds of carbon in furnace gas per pound of combustible consumed.

The average of B for 10 consecutive tests reported in Table 2 was 0.062. For the extreme case that the combustible matter in the refuse is 100 per cent carbon:

$$A=B$$

$$\text{and } \frac{C-A}{1-B}=\frac{C-B}{1-B}$$

$$\text{When } \quad C=0.900$$

$$\frac{C-B}{1-B}=0.893$$

The error for A_s resulting from the assumption that the composition of the combustible matter in the ash is the same as that in the coal as fired is less than $0.900-0.893=0.007$ or 0.8 per cent.

No attempt has been made to determine the amount of combustible matter carried in the flue gas in the form of soot or tar, so that the error arising from that source can not be estimated. Incandescent particles were never visible in the gases at the exit end of the combustion chamber and the amount of combustible matter lost in this way is probably negligible.

The weight of nitrogen contained in a pound of coal is small compared with the weight of nitrogen in the air required to burn a pound of coal, and the error due to the nitrogen of the coal is negligible.

RELATION BETWEEN CARBON DIOXIDE IN FURNACE GAS AND AIR.

Introducing the expression for A_s given above in the expression for "Percentage of excess air," the latter becomes:

$$\text{Percentage of excess air}=100\times\frac{3.03C\frac{N_2}{CO_2+CO+CH_4}-A_r}{A_r}$$

Here C and A_r depend on the composition of the fuel and are constant for a given fuel. When combustion is complete or nearly so, CO and CH_4 are negligible compared with CO_2, and N_2 is nearly constant. Under these conditions the equation reduces to the form:

$$\text{(1)} \qquad \text{Percentage of excess air}=\frac{D}{CO_2}-100$$

$$\text{In which } \quad D=\frac{100\times3.03\times C\times N_2}{A_r}$$

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D depends on the character of the fuel and, except for slight variations in N_2, is constant for a given fuel.

Equation 1 indicates a simple relation between percentage of excess air and CO_2 in the furnace gas, and furnishes a means of calculating the percentage of excess air from the CO_2 content of the furnace gas. By means of the relation given above, the constant D may be calculated from the ultimate analysis of the fuel, or in case the percentage of excess has been previously determined for a number of tests by means of the expression given on page 29, D may be calculated from the simultaneous values of "percentage of excess air" and of CO_2 by means of equation 1.

That there is a definite relation between the percentage of excess air and of CO_2 may be seen in figure 12 in which the values for the

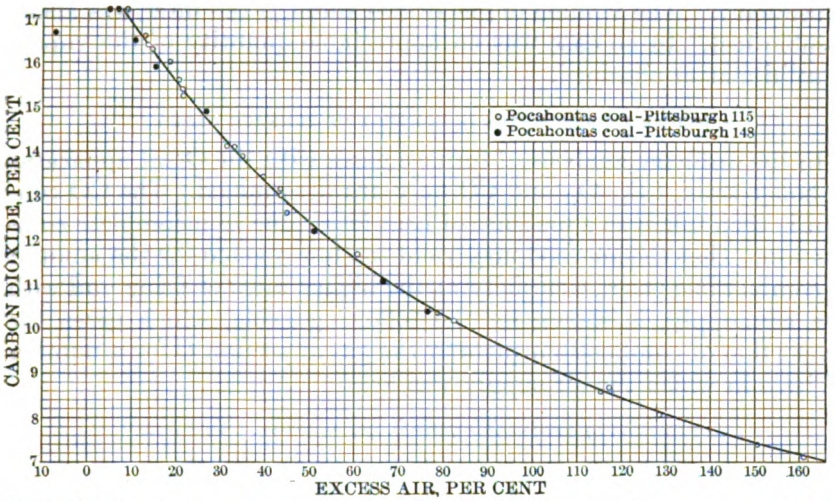

FIGURE 12.—Relation between percentage of carbon dioxide in furnace gas and percentage of excess air.

percentage of excess air and of CO_2 for the tests with Pocahontas coal are plotted respectively as abscissas and ordinates. The curve in the figure corresponds to the equation:

$$\text{Percentage of excess air} = \frac{1862}{CO_2} - 100 \qquad (2)$$

Both of the methods given for the calculation of the constant D gave the same result, namely, 1862. In calculating D by the first method mentioned, the mean of the ultimate analyses of the car samples of the two cars was used, and for N_2 (the nitrogen content of the furnace gas) the value 80.9, the average value for all the tests, was taken.

The close agreement between the values for percentage of excess air calculated by means of the complicated formula given on page 30, and

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that shown in figure 12 by the curve obtained by means of equation 1, indicate that the equation furnishes a rapid and reliable method for calculating the percentage of excess air from the CO_2 content of the furnace gas, provided the CO and CH_4 contents of the furnace gas are negligible.

UNSATURATED HYDROCARBONS, TAR, AND SOLID MATTER.

All samples taken at sections A and B were tested for unsaturated hydrocarbons. In no case was a measurable quantity of such gases found.

In tests 120 to 125 an attempt was made to determine the amounts of condensible vapors and of solid matter carried in the furnace gases. The special apparatus previously mentioned (p. 18) was used, the sample tube being introduced through the hole in the side wall of section A. The volume of gas drawn through the filter was about 3 cubic feet. In no case was an appreciable quantity of the vapors or solid matter obtained.

HYDROGEN AND METHANE CONTENT OF FURNACE GASES.

In the ordinary analysis of furnace gases with the Orsat apparatus in boiler tests, CO_2, O_2, and CO only are determined. The CO content is then taken as a measure of heat losses due to incomplete combustion. That this method may yield too low a value for the amount of combustible gases, especially at the higher rates of firing and with low air supply, is shown by the following table, which gives the proportion of combustible gases in the gas at section C for a number of tests in which the air supply was low:

Proportion of combustible gases in gas at section C in 5 tests.

Number of test.	CO_2 at section H.	Combustible gases at section C.		
		CO	H_2+CH_4	$\frac{H_2+CH_4}{CO}$
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
117	16.7	3.1	1.1	0.35
118	17.2	1.4	.3	.21
120	15.9	.8	.3	.37
121	17.2	1.3	.5	.38
125	16.5	1.1	.3	.27

DISCUSSION OF RESULTS OF TESTS.

In the tests described in this report effort was made to determine the effect of the two factors, rate of firing and air supply, on the volume of combustion-chamber space required for the complete combustion of Pocahontas coal. As far as possible all other factors were kept constant. A group of three or more tests were made at each rate of firing, the individual tests of each group differing from one another in the amount of air supplied per pound of combustible.

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INFLUENCE OF AIR SUPPLY ON SPACE REQUIRED FOR COMPLETE COMBUSTION.

Curves representing the variation of the combustible content of the gas with the volume of combustion space through which the gases have passed are given in figures 13 to 18. In these curves the abscissas represent the volume of combustion space and the ordinates the total combustibles ($CO + H_2 + CH_4$) contained in the gas. Each figure gives the results of tests at a particular rate of firing and each individual curve corresponds to a particular test and air supply.

A comparison of the curves in figures 13 to 18 shows clearly that, at a given rate of firing, as the air supply is increased, the time, and therefore the volume of the combustion chamber requisite for complete combustion, decreases rapidly. Thus, with an average rate of firing of 45.8 pounds (see fig. 16) in test 118, in which the CO_2 con-

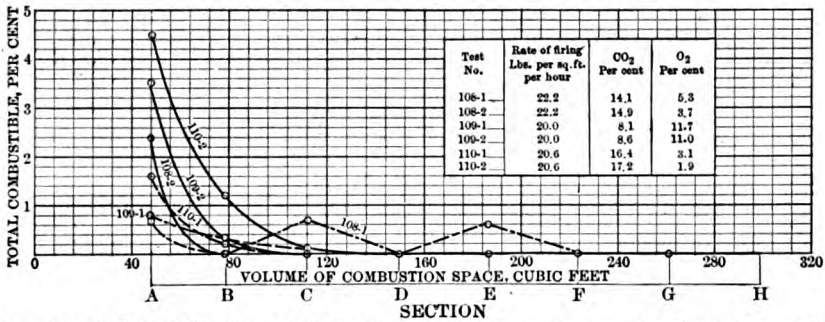

FIGURE 13.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 20.9 pounds of coal per square foot per hour.

tent of the furnace gas was 17.2 per cent and the oxygen content 1.7 per cent, the volume of combustion-chamber space required for practically complete combustion was 200 cubic feet, whereas in test 119, in which the rate of firing was 47.1 pounds and the furnace gas contained 12.2 per cent CO_2 and 7.5 per cent O_2, the combustible gases were consumed in a space of less than 80 cubic feet. Similarly with a rate of firing of 58.9 pounds (fig. 17), when the furnace gas contained not more than 11.1 per cent CO_2, 100 cubic feet of combustion-chamber space was sufficient for complete combustion; whereas in test 120, in which the furnace gas had a CO_2 content of 15.9 per cent after passing through the combustion chamber, which had a volume of 300 cubic feet, the gases contained 0.2 per cent of combustible constituents.

The curves in figures 13 to 18 indicate that there are a number of exceptions to the rule that the lower the air supply the greater the amount of space required for complete combustion. With the same rate of firing the combustible content of the gas at a given point in the combustion chamber is in some instances greater with a high air

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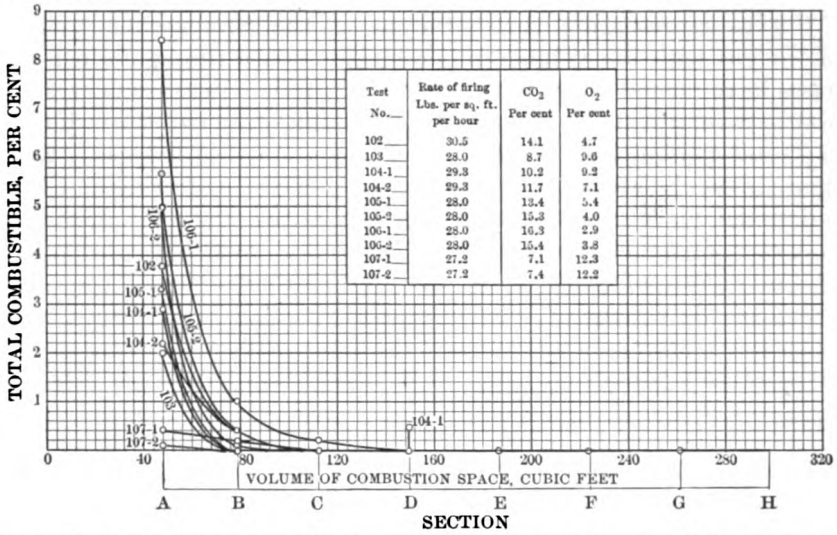
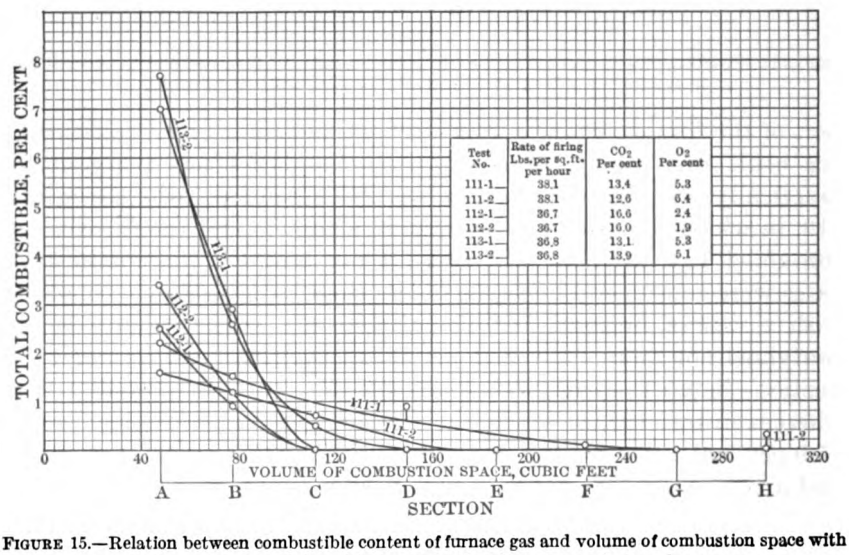
supply than with a low one. This result is doubtless due to inadequate control of air supply as well as rate of firing. As stated above,



Test No.	Rate of firing Lbs. per sq. ft. per hour	CO_2 Per cent	O_2 Per cent
102	30.5	14.1	4.7
103	28.0	8.7	9.6
104-1	29.3	10.2	9.2
104-2	29.3	11.7	7.1
105-1	28.0	13.4	5.4
105-2	28.0	15.3	4.0
106-1	28.0	16.3	2.9
106-2	28.0	15.4	3.8
107-1	27.2	7.1	12.3
107-2	27.2	7.4	12.2

FIGURE 14.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 28.4 pounds of coal per square foot per hour.

fluctuations of several per cent in the CO_2 content of the furnace gas were unavoidable.



Test No.	Rate of firing Lbs. per sq. ft. per hour	CO_2 Per cent	O_2 Per cent
111-1	38.1	13.4	5.3
111-2	38.1	12.6	6.4
112-1	36.7	16.6	2.4
112-2	36.7	16.0	1.9
113-1	36.8	13.1	5.3
113-2	36.8	13.9	5.1

FIGURE 15.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 37.2 pounds of coal per square foot per hour.

On account of the mechanical difficulties involved in taking such a large number of gas samples simultaneously, the period of sampling was made short—about eight minutes. In the earlier part of the

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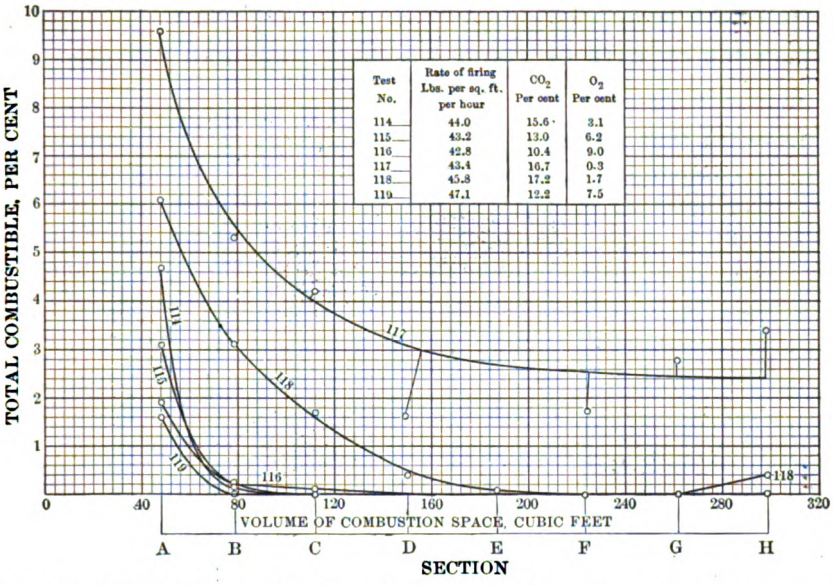
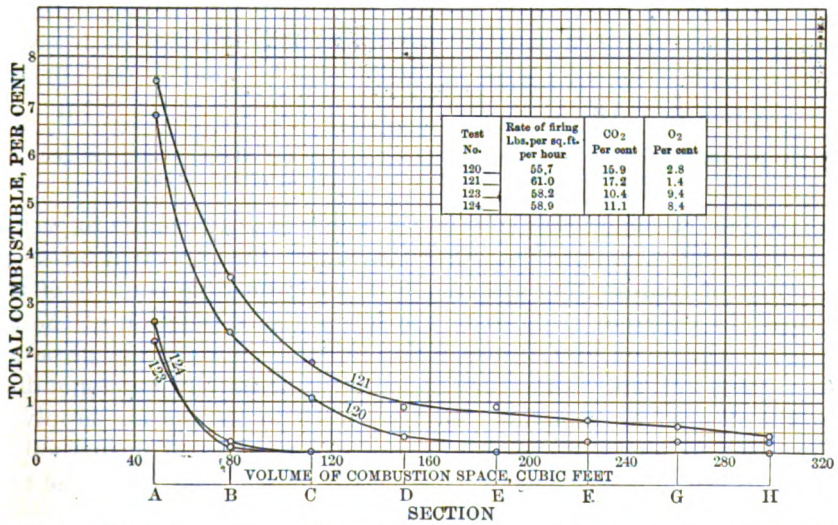
work it was not anticipated that this short period would result in serious errors. Experience showed, however, that on account of



Test No.	Rate of firing Lbs. per sq. ft. per hour	CO_2 Per cent	O_2 Per cent
114	44.0	15.6	3.1
115	43.2	13.0	6.2
116	42.8	10.4	9.0
117	43.4	16.7	0.3
118	45.8	17.2	1.7
119	47.1	12.2	7.5

FIGURE 16.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 44.3 pounds of coal per square foot per hour.

unavoidable variations in the drafts and the condition of the fuel bed, the rate of combustion over as short a period as eight minutes


TOTAL COMBUSTIBLE, PER CENT
VOLUME OF COMBUSTION SPACE, CUBIC FEET
SECTION
A B C D E F G H
0 40 80 120 160 200 240 280 320
1 2 3 4 5 6 7 8
124
123
121
120

Test No.	Rate of firing Lbs. per sq. ft. per hour	CO_2 Per cent	O_2 Per cent
120	55.7	15.9	2.8
121	61.0	17.2	1.4
123	58.2	10.4	9.4
124	58.9	11.1	8.4

FIGURE 17.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 58.4 pounds of coal per square foot per hour.

may vary considerably from the average rate during the test, and consequently that the average rate of combustion for the test is not

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always an accurate measure of the actual rate during a short period of sampling. It is hoped that in future tests the period of sampling may be so lengthened as to overcome this source of error.

INFLUENCE OF RATE OF FIRING ON SPACE REQUIRED FOR COMPLETE COMBUSTION.

In order that results of tests with different rates of combustion may be comparable, it is essential that the test so compared be made with the same air supply. If, for example, at each rate of firing tests could be made with exactly 10, 12, 14, and 16 per cent CO_2, the several series of tests would be directly comparable. Unfortunately,

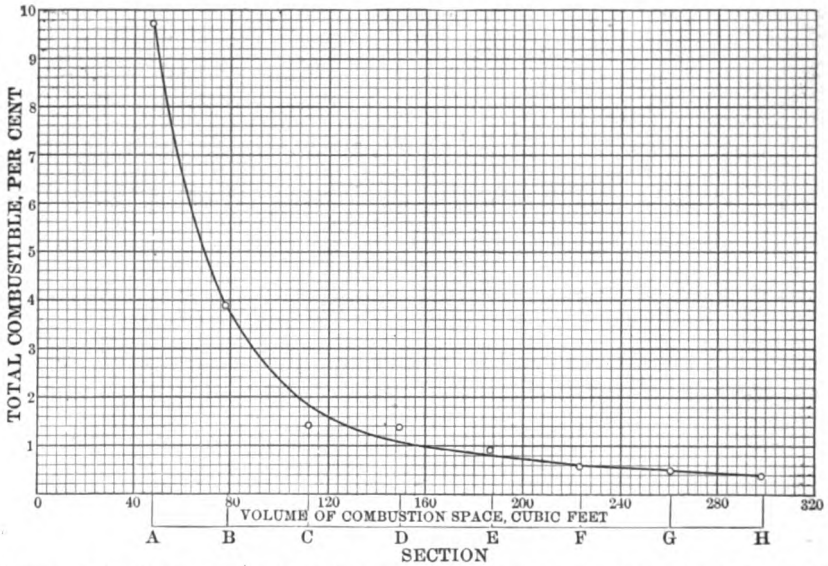

FIGURE 18.—Relation between combustible content of furnace gas and volume of combustion space with an average rate of firing of 65.4 pounds of coal per square foot per hour.

it is not practicable to control the air supply exactly enough to permit any such direct comparison. For this reason the expedient has been adopted of representing graphically the combustible content of the gas at the different sections of the furnace as a function of the air supply, and then, by interpolation of the curves thus obtained (figs. 19 to 21), find values for the combustible content corresponding to the desired air supplies. In figures 19 to 21 the air supply is expressed in terms of "percentage of excess air." The method of computing the percentage of excess air from the analysis of the fuel and the fuel gas has been shown above.

In figures 19 and 20 for sections A and B of the combustion chamber each curve corresponds to a particular rate of firing. At section C and beyond combustible constituents were found in the gas only

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at the highest rate of firing. The curves for sections C, D, E, F, G, and H are therefore combined in one figure (fig. 21). The curves in figures 19 to 21 exhibit, in every case, a rapid decrease in the combustible content of the gas at a given section of the furnace, with increase in the percentage of excess air.

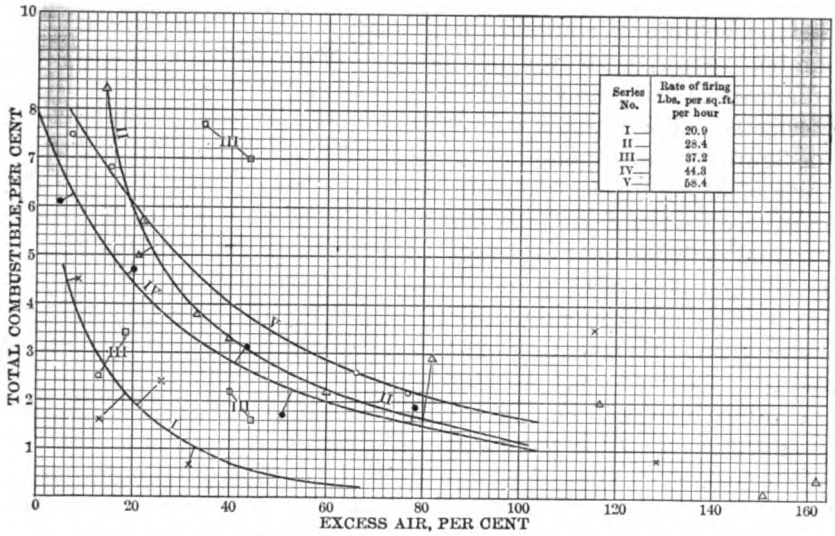

FIGURE 19.—Relation between combustible content of gas and air supply, section A.

The curves in figures 22 to 25 were plotted from data obtained by interpolation of the curves in figures 19 to 21. They show the decrease in the combustible content of the gas during its passage through the combustion chamber. As the air supply is the same for

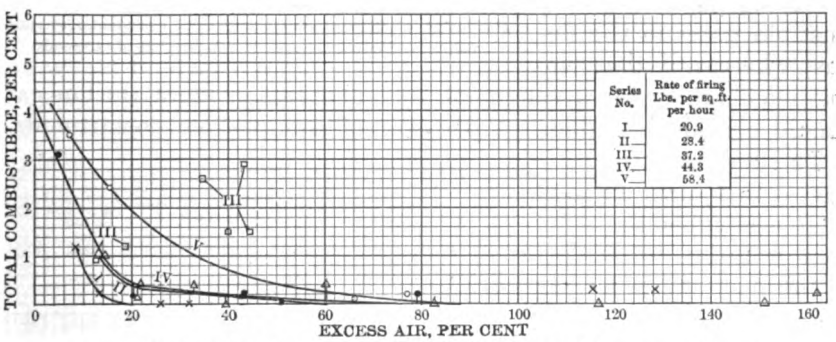

FIGURE 20.—Relation between combustible content of gas and air supply, section B.

all the curves in any one figure, the results for different rates of firing are directly comparable. From these curves the volume of combustion-chamber space required for the complete combustion of Pocahontas coal, under the conditions for mixing of air and of heat-

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ing the fuel in the equipment used in these tests, may readily be determined. The intersection of any given curve in one of figures 22 to 25 with the horizontal line corresponding to the "percentage of total combustible" that shall not be exceeded in the flue gas gives the volume of combustion chamber required for the particular rate of firing and air supply selected. For example, curve V of figure 24, corresponding to a rate of firing of 58.4 pounds per square foot of grate area per hour, and to 50 per cent of excess air (12.4 per cent of CO_2), intersects the line for zero combustible at the point representing 110 cubic feet, the line for 0.1 per cent of combustible at the point representing 96 cubic feet, and the line for 0.3 per cent of combustible at the point representing 82 cubic feet. Accordingly, when Pocahontas coal is burned at a rate of about 60 pounds per hour and with 50 per cent of excess air, if the volume of the combustion chamber is 80 cubic feet, one should expect to find about 0.3 per cent of combustible gases in the flue gas; whereas, if the combustion chamber has a volume of 100 cubic feet or more, the flue gas should contain less than 0.1 per cent of combustible constituents.

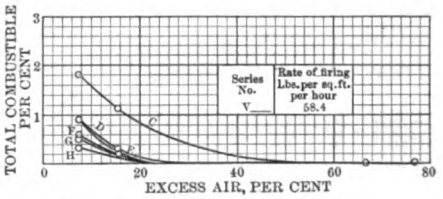

FIGURE 21.—Relation between combustible content of gas and air supply, sections C to H.

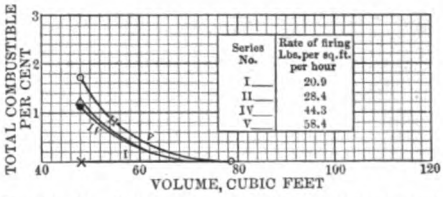

FIGURE 22.—Relation between combustible content of gas and volume of combustion space for 100 per cent of excess air.

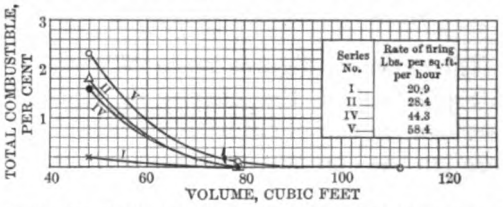

FIGURE 23.—Relation between combustible content of gas and volume of combustion space for 75 per cent of excess air.

To illustrate the use of curves in figures 22 to 25, let it be assumed that a furnace is to be run with 50 per cent of excess air, corresponding to 12.4 per cent of CO_2 in the flue gas, and that the combustible content of the flue gas is not to exceed 0.2 per cent. The relation between the volume of combustion space required and the rate of firing as obtained from the curve for 50 per cent of excess air in figure 24 is as follows:

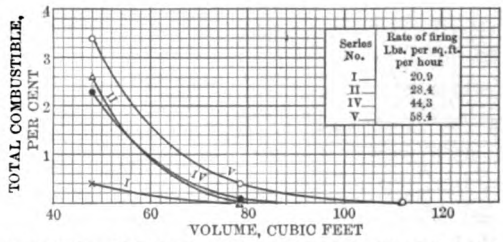

FIGURE 24.—Relation between combustible content of gas and volume of combustion space for 50 per cent of excess air.

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Relation between volume of combustion space and rate of firing as determined from figure 24.

Coal per square foot per hour.	Volume of combustion space.	Ratio of volume of combustion space to grate area.
Pounds.	*Cubic feet.*	
20.9	58	2.3
28.4	73	2.9
44.3	75	3.0
58.4	88	3.5

For a rate of firing of 28.4 pounds of coal per square foot per hour, a combustion space of 2.9 cubic feet per square foot of grate area should be sufficient to reduce the combustible content of the flue gas to 0.2 per cent. If, however, the rate of firing should be doubled, curve V in figure 24 shows that the combustible content of the flue

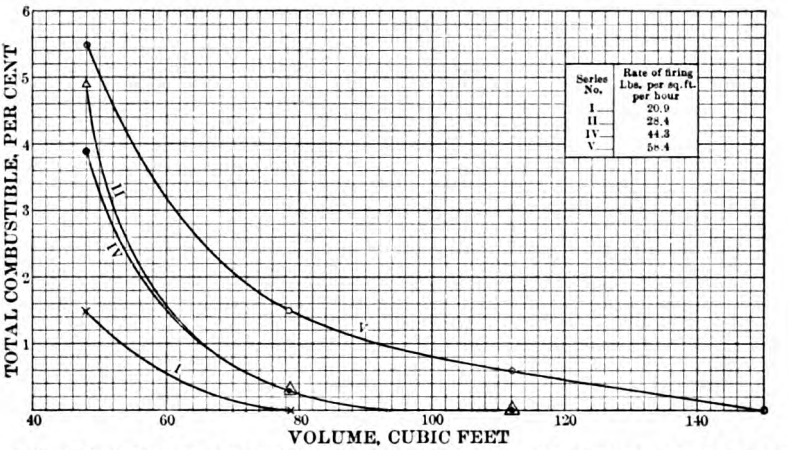

FIGURE 25.—Relation between combustible content of gas and volume of combustion space for 25 per cent of excess air.

gas would be over 0.6 per cent, and, consequently, the heat loss due to incomplete combustion would be more than 4 per cent. Practically complete combustion may be obtained, however, with a rate of firing of 60 pounds if the combustion space is more than 5 cubic feet per square foot of grate area.

INFLUENCE OF THE DEGREE OF MIXING OF AIR WITH COMBUSTIBLE GASES ON SPACE REQUIRED FOR COMBUSTION.

In the foregoing pages the influence of two factors—rate of firing and air supply—on the volume of combustion chamber required for the combustion of coal in boiler furnaces has been considered. Two other factors—the degree of mixing of air and combustible gases, and the rate of heating of the fuel—are of great importance. In the language of the kinetic theory, each individual particle of gaseous, liquid, or solid material in the furnace gas must come in contact with the required number of oxygen molecules, furnished by the air,

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before oxidation or combustion can take place. The rate of combustion is, therefore, proportional to the number of impacts between combustible particles and oxygen molecules. The more frequent these impacts the shorter will be the time and the smaller the space that is required for combustion. If in passing through the long combustion chamber of the furnace used in these tests the gases move in parallel straight lines, impacts would be far less frequent than if the gases were subjected to a vigorous mechanical mixing. The series of tests reported herein was made without the use of any special mixing device. However, a violent circulation of the furnace gases was produced by the currents of air entering the furnace. The character of the whirling motion of the gases leaving the fire box, which may be readily observed through the observation hole in the side wall of the Heine boiler, is indicated in figure 26. In the figure A represents a current of air rising from the ash pit; B and B represent currents of air introduced over the top of the fuel bed through openings at the base of the furnace arch. It is not improbable that placing mixing structures in the combustion chamber back of the grate to deflect the flow lines of the gases would diminish the time and space required for complete combustion.

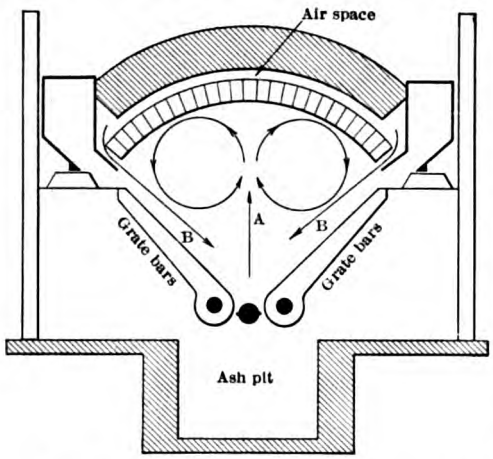

FIGURE 26.—Section through stoker showing mixing of gases caused by currents of air.

A series of tests to determine the effect of variations in the method of mixing the air and furnace gases is contemplated as a part of the general investigation of the combustion of fuel. One of the difficulties in the way of the successful use of mixing structures in the combustion chamber, especially at the higher rates of firing, is that of obtaining materials that will withstand the high temperatures of the furnace gases.

INFLUENCE OF RATE OF HEATING COAL ON SPACE REQUIRED FOR COMBUSTION.

The composition, as well as the amount, of volatile matter given up by a given coal varies greatly with the temperature to which the coal is heated and the rate of heating. The influence of temperature on the amount and composition of the volatile matter distilled from various coals has been studied by Porter and Ovitz of the Bureau

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of Mines.[a] They found, for example, the following values for the volume of combustible gas given off in 10 minutes from 10 grams of air-dried Pocahontas coal:

Relation of temperature of furnace to volume of combustible gas.

Temperature of furnace, ° C	600	700	800	900
Volume of combustible gas, c. c	50	670	1,570	2,300

The amount of tar produced increases with increase of temperature in about the same proportion as does the volume of combustible gases.

The heavier constituents of the volatile matter, especially the tar, do not burn readily and require more time for combustion. The higher the temperature at which distillation takes place, therefore, the greater is the amount of volatile matter drawn off and the more difficult is the combustion of its constituents. A rapid rate of heating of the fuel produces a rapid evolution of slow-burning volatile matter. A slow rate of heating results in a gradual and uniform liberation of volatile gases, which are more readily combustible. One advantage in the use of the automatic stoker over hand firing is that in the automatic stoker the coal is heated gradually through the temperatures at which distillation takes place, whereas in hand firing the green fuel is thrown directly on the incandescent fuel bed and thus is suddenly heated from room temperature to the temperature of the furnace.

In the tests described in this report the supply of coal was regulated automatically and the rate of heating was constant for each rate of firing. In a future investigation it is planned to vary the rate of heating the coal and to study the relation between the rate of heating and the volume of combustion space required.

THICKNESS OF FUEL BED.

With the type of stoker used in the tests the coal is fed continually to the grate, and with proper regulation of the speed of the stoker engine the thickness of fuel bed may be kept fairly constant. In the tests with Pocahontas coal the thickness of bed carried was about 6 inches. No attempt has been made to study the relation between different thicknesses of fuel bed and the space required for combustion. There is ample evidence at hand to show that excessive thickness of bed favors the formation of CO by the reaction: $CO_2 + C = 2CO$, the reaction that takes place in the gas producer. Increasing the thickness of the fuel bed, therefore, not only reduces the combustion space above the bed but produces greater quantities of CO, and thus increases the volume of combustion-chamber space required.

[a] Porter, H. C., and Ovitz, F. K., The volatile matter of coal: Bull. 1, Bureau of Mines, 1910, 56 pp., 1 pl., 9 figs.

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